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April 1980

LEVEL III

ROME AIR DEVELOPMENT CENTER

ACOSS FOUR (ACTIVE CONTROL OF SPACE STRUCTURES) THEORY. APPENDIX

The Charles Stark Draper Laboratory, Inc.

Sponsored by
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ARPA Order No. 3654

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

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APPROVED: Richard W. Carman
RICHARD W. CARMAN
Project Engineer

ACOSS FOUR (ACTIVE CONTROL OF
SPACE STRUCTURES) THEORY APPENDIX

R.R. Strunce
D.R. Hegg
J.G. Lin
T.C. Henderson

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Principal Investigator: Robert R. Strunce
Phone: 617-258-1547

Project Engineer: Richard W. Carman
Phone: 315-330-3148

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is the Charles Stark Draper Laboratory, Inc., final technical report on its Actively Controlled Structures Theory Study. The objective of the research reported here was to develop the theoretical and analytical tools to support the successful implementation of active vibration control of large flexible spacecraft. Parallel efforts in theory and applications were initiated. For the theoretical effort, several representative design methods were selected for careful study focusing on an (over)

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examination of the theoretical basis for each method and potential difficulties associated with their use in reduced-order large space structure controller design. The methods initially selected are characterized by constant-gain output feedback, the simplest form of active multivariable control; (1) Modal Decoupling, (2) Pole Assignment, (3) Optimal Output Feedback, (4) Suboptimal Output Feedback, (5) Stochastic Optimal Output Feedback. A performance comparison of specific designs with these methods was made. Extensions to the published Kosut methods of suboptimal output feedback are developed, as well as the details of an algorithm necessary for a numerical solution. Techniques and conditions are developed for reduction of control (observation) spillover by placement of actuators (sensors), by synthesis of the actuator (sensor) influences, and by compensation of acutators (sensors). For the applications effort, relatively high order models representative of the large space structures of interest were employed. Effectiveness of both passive and active local member dampers as well as modern modal controller feedback designs for inducing vibration damping, was studied by simulation. A simple structural model (tetrahedron) was developed for the purpose of evaluating various large space structure control methods.

ACKNOWLEDGMENT

The work reported herein was performed by The Charles Stark Draper Laboratory, Inc. (CSDL) under Contract F30602-78-C-0268. The research was supported by the Advanced Research Projects Agency of the Department of Defense, and was monitored by the Rome Air Development Center. This final report covers the time period from 24 July 1978 to 31 December 1979. The technical monitors of this program are Major A. Herzberg and Mr. D. Carman.

The Program Manager is Dr. Keto Soosaar and the Principal Investigator is Mr. Robert Strunce. This study was performed within the Advanced Systems Department headed by Mr. David Hoag. The contributors to this report are Dr. Jiguan G. Lin (Section 2), Dr. Daniel R. Hegg (Sections 1, 3), Mr. Robert R. Strunce (Sections 1, 4), and Mr. Timothy C. Henderson (Appendix A).

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APPENDIX A

TETRAHEDRAL MODEL

A.1 Introduction

In order to evaluate and compare the various methods for structural control of large space structures (LSS), a simple evaluation model was created. The goal in the design of this model was to retain many of the characteristics of a typical LSS, and at the same time, keep the order of the problem small (less than 20 modes). The resulting model, shown in Figure A-1, meets these design requirements. The structure is similar in form to typical optical and radar systems. The performance criterion for this system is the motion of Node 1 at the apex of the tetrahedron. This is analogous to the line-of-sight error performance measure of typical LSS optical systems. This model has 12 dynamic degrees of freedom, and thus a maximum of 12 modes. This results in low-order design and evaluation models, which can easily be used to evaluate a variety of control systems.

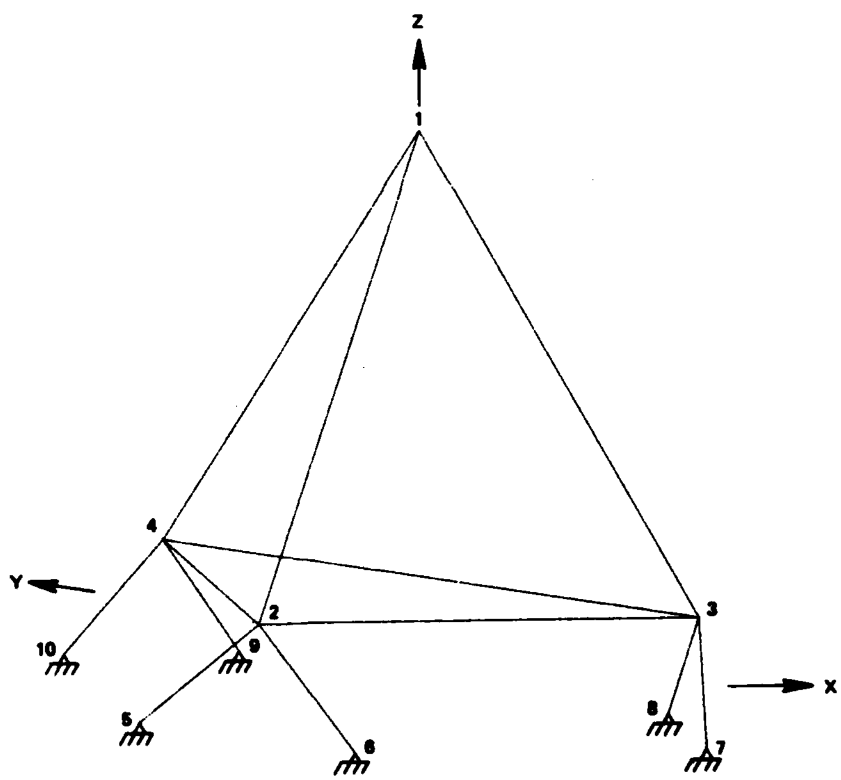

Figure A-1. Tetrahedral finite-element model.

A.2 Finite-Element Model

The finite-element model of the structure is shown in Figures A-1 and A-2. It is a tetrahedron supported by six legs, which are pinned to the ground. The system is ground-supported because attitude control is not of concern at this time. The global coordinates of each node point are listed in Table A-1. All joints are pin connections, that is, capable of transmitting only axial member forces. Table A-2 lists the nodal connectivity and cross-sectional area of each element. A Young's modulus value of one has been used to simplify the stiffness computation. Masses are lumped at Nodes 1 through 4 and are listed in Table A-3.

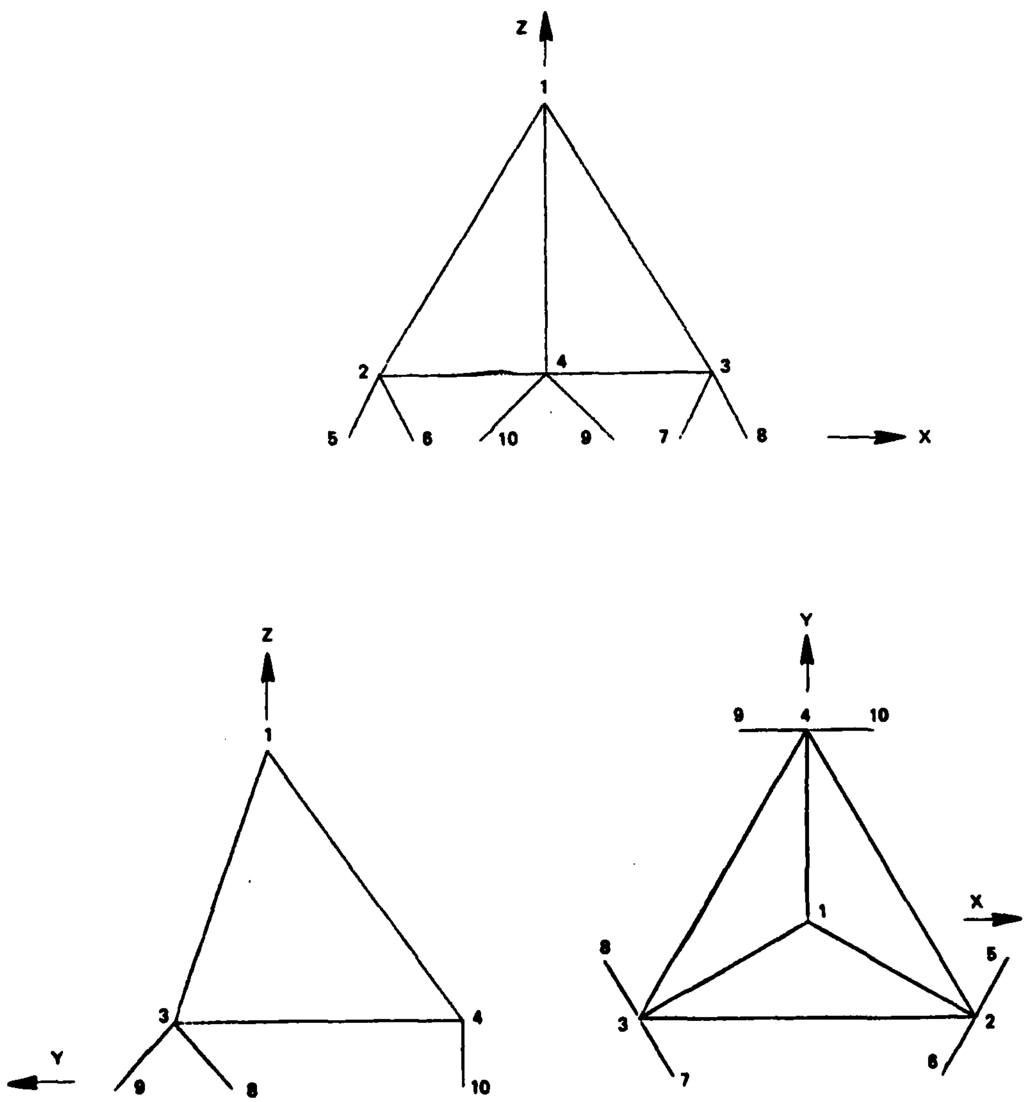

Figure A-2. Tetrahedral finite-element model—ground-supported by six legs.

Table A-1. Node point coordinates.

Node	X	Y	Z
1	0.0	0.0	10.165
2	-5.0	-2.887	2.00
3	5.0	-2.887	2.00
4	0.0	5.7735	2.00
5	-6.0	-1.1547	0.0
6	-4.0	-4.6188	0.0
7	4.0	-4.6188	0.0
8	6.0	-1.1547	0.0
9	2.0	5.7735	0.0
10	-2.0	5.7735	0.0

Table A-2. Element connectivities and areas.

			Cross-Sectional Area	
Element	Node 1	Node 2	Nominal Case	Perturbed Case
1	1	2	1000.	1200.
2	1	3	100.	150.
3	1	4	100.	150.
4	2	3	1000.	1200.
5	3	4	1000.	1200.
6	2	4	1000.	1200.
7	2	5	100.	150.
8	2	6	100.	150.
9	3	7	100.	150.
10	3	8	100.	150.
11	4	9	100.	150.
12	4	10	100.	150.

Table A-3. Nodal lumped masses.

	Lumped Mass	
Node	Nominal Case	Perturbed Case
1	2.0	4.0
2	2.0	2.0
3	2.0	2.0
4	2.0	2.0

A modal analysis was performed using NASTRAN. The printout of this analysis, which contains the input data and the resulting natural frequencies and mode shapes, is reproduced in Section A.3. Computer plots of the mode shapes are given in Figure A-3.

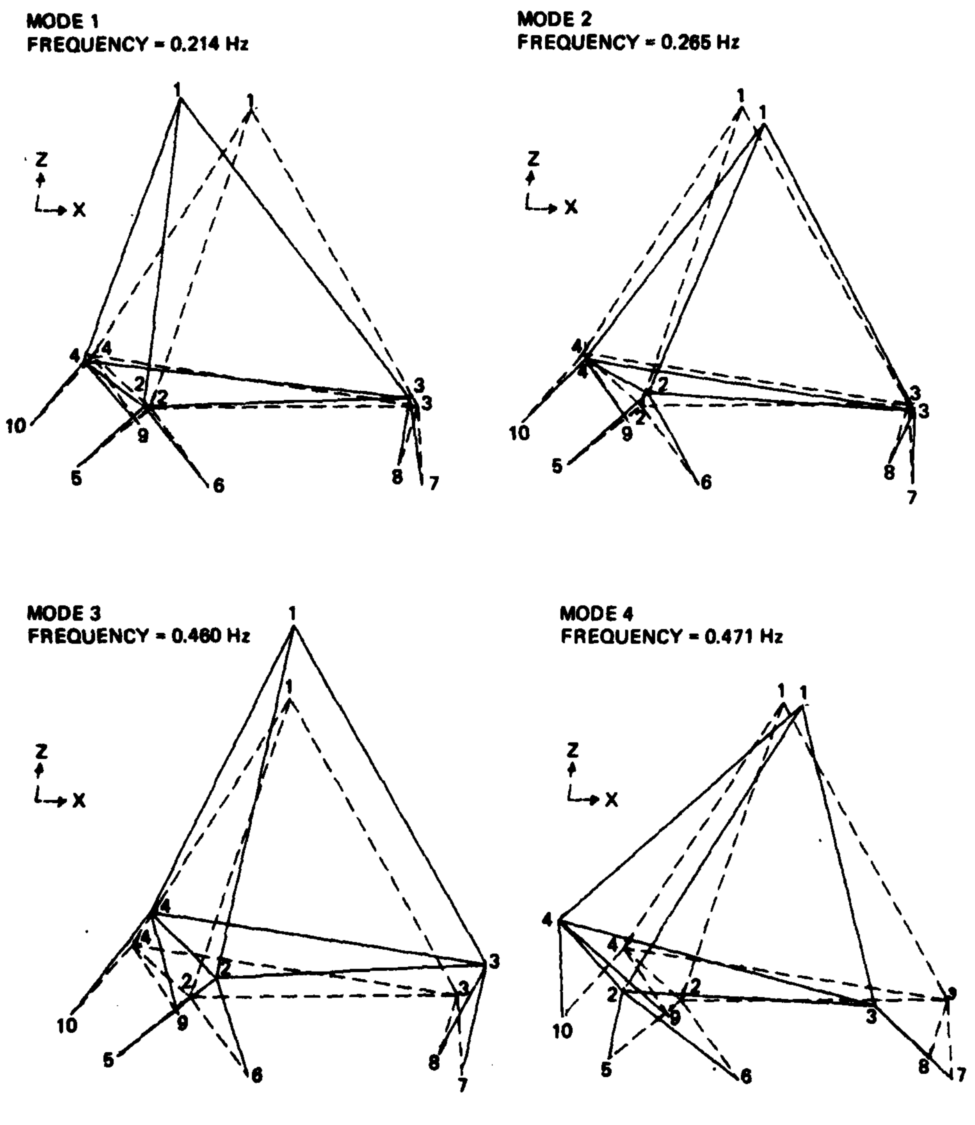

Figure A-3. Mode shapes—nominal configuration.

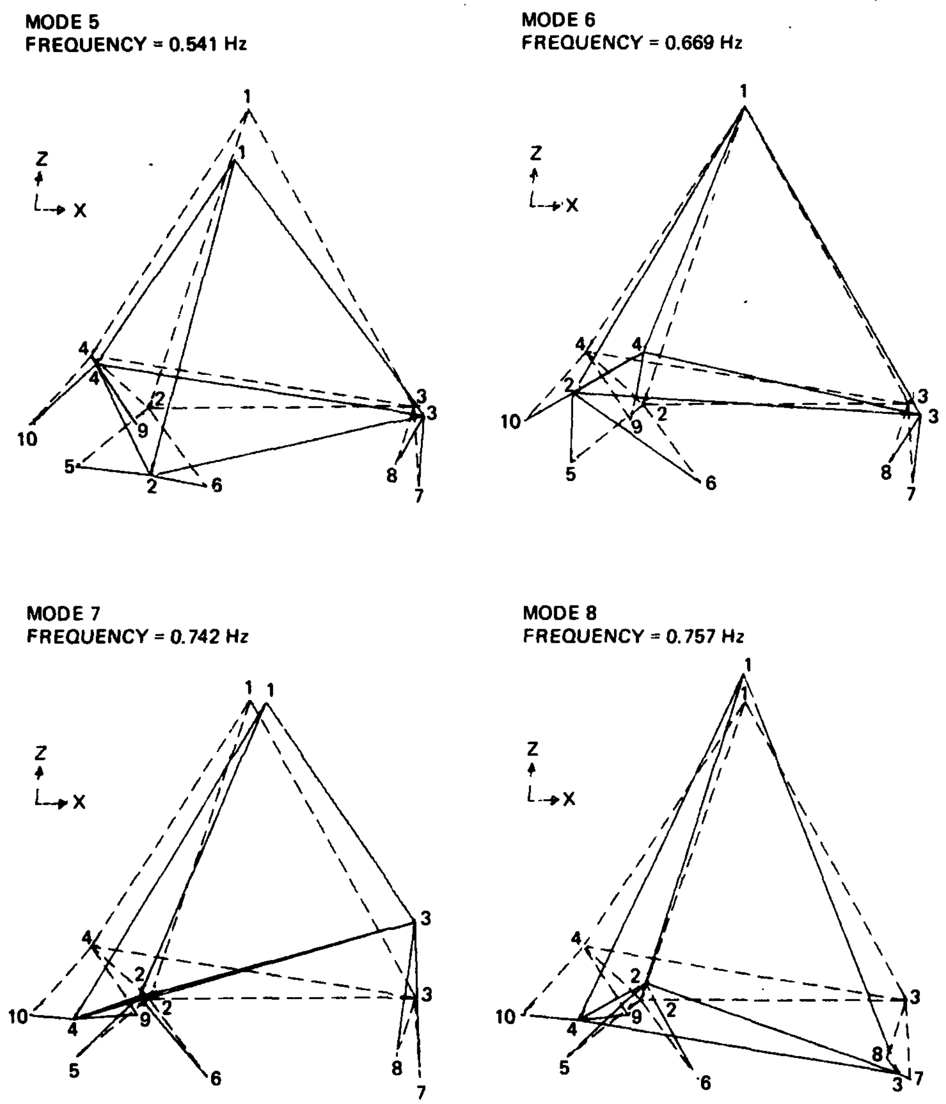

Figure A-3. Mode shapes—nominal configuration. (Cont.)

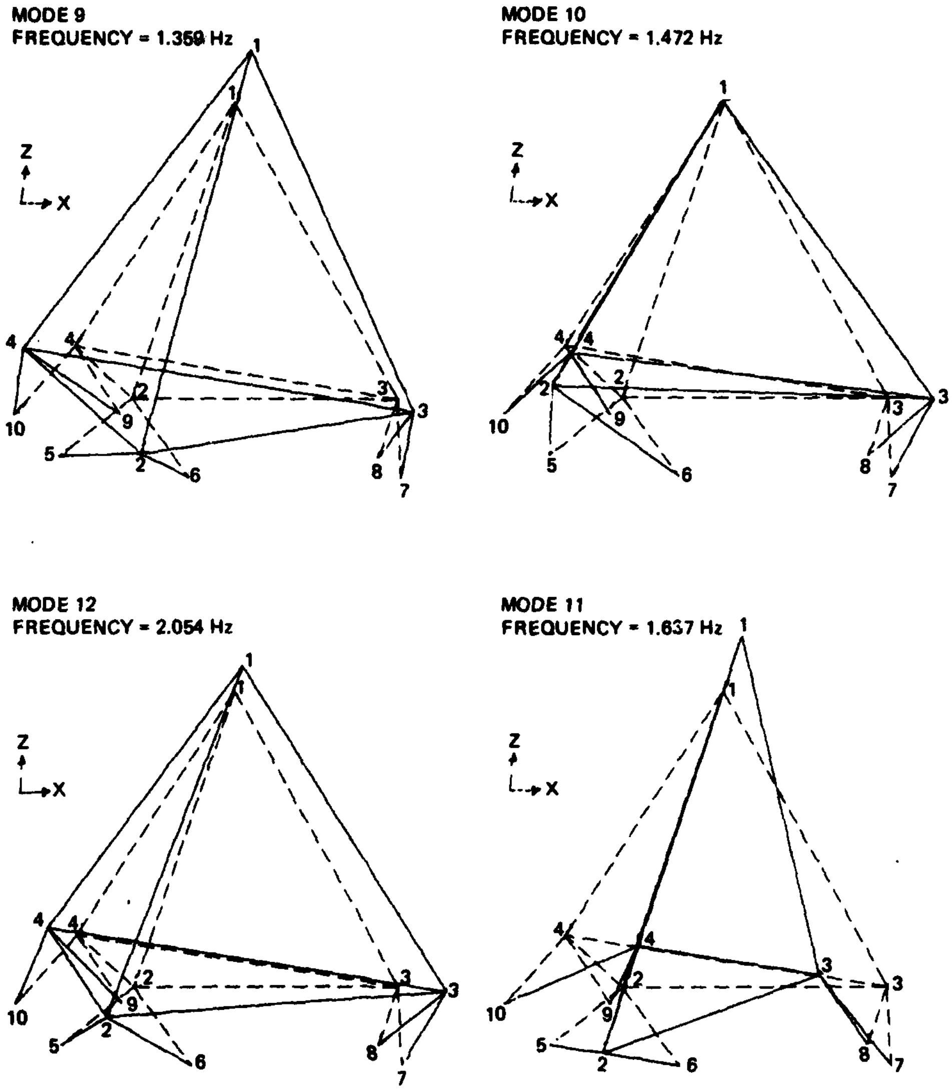

Figure A-3. Mode shapes—nominal configuration. (Cont.)

In order to evaluate the sensitivity of the control system to variations in the system frequencies and mode shapes, a perturbed model was created by varying selected mass and stiffness properties. The new lumped masses and member cross-sectional areas are listed in Table A-3 along with the nominal configuration. A modal analysis of this model was performed. The natural frequencies are listed in Table A-4 for easy comparison with the nominal case. The NASTRAN printout for the perturbed structure is reproduced in Section A-4, and contains a complete listing of the input data and the new natural frequencies and mode shapes.

Table A-4. Modal natural frequencies.

Mode	Nominal Case		Perturbed Case	
	rad/s	Hz	rad/s	Hz
1	1.342	0.2136	1.171	0.1863
2	1.665	0.2650	1.467	0.2334
3	2.891	0.4601	2.965	0.4718
4	2.957	0.4707	3.558	0.5662
5	3.398	0.5408	3.848	0.6125
6	4.204	0.6692	5.149	0.8196
7	4.662	0.7420	5.676	0.9033
8	4.755	0.7568	5.711	0.9089
9	8.539	1.359	8.940	1.423
10	9.250	1.472	10.030	1.640
11	10.285	1.637	10.923	1.739
12	12.905	2.054	13.966	2.223

A.3 NASTRAN Listing for Nominal Configuration

N A S T R A N

MSC -48B

VERSION JUN 7, 1979

CDC 170 SERIES

MODEL CYBER175-2

ACS

N A S T R A N   E X E C U T I V E   C O N T R O L   D E C K   E C H O

```
ID TRUSS SIM.,BICKFORD
SOL 25
TIME 1.5
CEND
```

```
                         C A S E   C O N T R O L   D E C K   E C H O
   CARD
   COUNT
     1      TITLE = ACOSS= DRAPER STRUCTURE
     2      SUBTITLE = NOMINAL CONFIGURATION
     3      DISPLACEMENT = ALL
     4      SPC = 100
     5      METHOD = 100
     6      BEGIN BULK

          TOTAL COUNT=   29

*** USER INFORMATION MESSAGE 207, BULK DATA NOT SORTED,XSORT WILL RE-ORDER DECK.
```

S O R T E D B U L K D A T A E C H O

CARD COUNT	. 1 ..	2 ..	3 ..	4 ..	5 ..	6 ..	7 ..	8 ..	9 ..	10 .
1-	CONM2	21	1		2.0					
2-	CONM2	22	2		2.0					
3-	CONM2	23	3		2.0					
4-	CONM2	24	4		2.0					
5-	CROD	1	6	1	2	2	5	1	3	
6-	CROD	3	5	1	4	4	6	2	3	
7-	CROD	5	6	3	4	6	6	2	4	
8-	CROD	7	5	2	5	8	5	2	6	
9-	CROD	9	5	3	7	10	5	3	8	
10-	CROD	11	5	4	9	12	5	4	10	
11-	FIGR	100	GIV				12			+AR
12-	+AR	MASS								
13-	GRDSET							456		
14-	GRID	1		.0	.0	10.165				
15-	GRID	2		-5.0	-2.887	2.00				
16-	GRID	3		5.0	-2.887	2.00				
17-	GRID	4		.0	5.7735	2.00				
18-	GRID	5		-6.0	-1.1547	.0				
19-	GRID	6		-4.0	-4.6188	.0				
20-	GRID	7		4.0	-4.6188	.0				
21-	GRID	8		6.0	-1.1547	.0				
22-	GRID	9		2.0	5.7735	.0				
23-	GRID	10		-2.0	5.7735	.0				
24-	MAT1	15	1.0							
25-	PARAM	GRDPNT	0							
26-	PROD	5	15	100.0						
27-	PROD	6	15	1000.0						
28-	SPC1	100	123	5	THRU	10				
	ENDDATA									

TOTAL COUNT= 28

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        N A S T R A N   S O U R C E   P R O G R A M   C O M P I L A T I O N
   DMAP-DMAP INSTRUCTION
    NO.

*** USER WARNING MESSAGE  27.
    LABEL NAMED JMPKGG   NOT REFERENCED
```

ACOSS= DRAPER STRUCTURE
NOMINAL CONFIGURATION

```
*** USER WARNING MESSAGE 3041

EXTERNAL GRID POINT        0 DOFS NOT EXIST OR IS NOT A GEOMETRIC GRID POINT.
THE BASIC ORIGIN WILL BE USED.
```

```
                    O U T P U T   F R O M   G R I D   P O I N T   W E I G H T   G E N E R A T O R

                                              REFERENCE POINT =        0
                                                   M O
 * 8.000000E+00  0.             0.             0.             3.233000E+01  1.000000E-03 *
 * 0.            8.000000E+00   0.            -3.233000E+01   0.            0.           *
 * 0.            0.             8.000000E+00  -1.000000E-03   0.            0.           *
 * 0.           -3.233000E+01  -1.000000E-03   3.306601E+02   0.            0.           *
 * 3.233000E+01  0.             0.             0.             3.306545E+02  2.000000E-03 *
 * 1.000000E-03  0.             0.             0.             2.000000E-03  2.000057E+02 *
                                                   S
                    * 1.000000E+00  0.             0.            *
                    * 0.            1.000000E+00   0.            *
                    * 0.            0.             1.000000E+00  *
      DIRECTION
   MASS AXIS SYSTEM (S)     MASS          X-C.G.          Y-C.G.         Z-C.G.
             X          8.000000E+00      0.         -1.250000E-04   4.041250E+00
             Y          8.000000E+00      0.          0.             4.041250E+00
             Z          8.000000E+00      0.         -1.250000E-04   0.
                                                  I(S)
                    * 2.000065E+02  0.             0.            *
                    * 0.            2.000008E+02   2.041250E-03  *
                    * 0.            2.041250E-03   2.000057E+02  *
                                                  I(Q)
                    * 2.000065E+02                               *
                    *               2.000008E+02                 *
                    *                              2.000057E+02  *
                                                   Q
                    * 1.000000E+00  0.             0.            *
                    * 0.            1.000000E+00   0.            *
                    * 0.            0.             1.000000E+00  *
```

E I G E N V A L U E   A N A L Y S I S   S U M M A R Y   (GIVENS METHOD)

```
NUMBER OF EIGENVALUES EXTRACTED . . . . . . . .          12
NUMBER OF EIGENVECTORS COMPUTED . . . . . . . .          12
NUMBER OF EIGENVALUE CONVERGENCE FAILURES . .             0
NUMBER OF EIGENVECTOR CONVERGENCE FAILURES. .             0

REASON FOR TERMINATION. . . . . . . . . . . .             1

LARGEST OFF-DIAGONAL MODAL MASS TERM. . . . .      5.33E-15

          MODE PAIR. . . . . . . . . . . . . .            9
                                         . . .            3
NUMBER OF OFF-DIAGONAL MODAL MASS
     TERMS FAILING CRITERION. . . . . . . . .             0
```

R E A L   E I G E N V A L U E S

MODE NO.	EXTRACTION ORDER	EIGENVALUE	RADIANS	CYCLES	GENERALIZED MASS	GENERALIZED STIFFNESS
1	5	1.800993E+00	1.342011E+00	2.135877E-01	1.000000E+00	1.800993E+00
2	6	2.771304E+00	1.664724E+00	2.649490E-01	1.000000E+00	2.771304E+00
3	11	8.356214E+00	2.890712E+00	4.600711E-01	1.000000E+00	8.356214E+00
4	10	8.746297E+00	2.957414E+00	4.706871E-01	1.000000E+00	8.746297E+00
5	9	1.154776E+01	3.398200E+00	5.408403E-01	1.000000E+00	1.154776E+01
6	12	1.767767E+01	4.204482E+00	6.691641E-01	1.000000E+00	1.767767E+01
7	8	2.173488E+01	4.662068E+00	7.419913E-01	1.000000E+00	2.173488E+01
8	7	2.261250E+01	4.755260E+00	7.568231E-01	1.000000E+00	2.261250E+01
9	3	7.292165E+01	8.539418E+00	1.359091E+00	1.000000E+00	7.292165E+01
10	4	8.557293E+01	9.250564E+00	1.472273E+00	1.000000E+00	8.557293E+01
11	2	1.057766E+02	1.028477E+01	1.636873E+00	1.000000E+00	1.057766E+02
12	1	1.665419E+02	1.290511E+01	2.053912E+00	1.000000E+00	1.665419E+02

ACOSS= DRAPER STRUCTURE NOVEMBER 30, 1979 NASTRAN 6/ 7/79 PAGE 11
NOMINAL CONFIGURATION

EIGENVALUE = 1.800993E+00

REAL EIGENVECTOR NO. 1

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	-3.444178E-01	5.964267E-01	2.330351E-06	0.0	0.0	0.0
2	G	-3.107025E-02	5.378755E-02	-1.110576E-05	0.0	0.0	0.0
3	G	-5.079280E-02	6.517632E-02	6.379659E-02	0.0	0.0	0.0
4	G	-3.106509E-02	7.656156E-02	-6.378554E-02	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 2.771304E+00

REAL EIGENVECTOR NO. 2

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	5.428831E-01	3.135075E-01	-1.989818E-01	0.0	0.0	0.0
2	G	1.262983E-01	7.291809E-02	9.756437E-02	0.0	0.0	0.0
3	G	1.097555E-01	4.162473E-02	-6.727581E-02	0.0	0.0	0.0
4	G	9.091599E-02	7.424605E-02	-6.728264E-02	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 8.356214E+00

R E A L   E I G E N V E C T O R   N O .   3

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	-4.920856E-02	-2.843651E-02	3.787649E-01	0.0	0.0	0.0
2	G	3.124646E-01	1.805227E-01	6.518569E-02	0.0	0.0	0.0
3	G	2.726652E-01	1.274398E-01	1.371336E-01	0.0	0.0	0.0
4	G	2.465888E-01	1.726462E-01	1.372212E-01	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 8.746297E+00

R E A L   E I G E N V E C T O R   N O .   4

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	5.725973E-02	-9.915034E-02	-1.466010E-04	0.0	0.0	0.0
2	G	-1.759619E-01	3.045818E-01	-7.204926E-05	0.0	0.0	0.0
3	G	-2.387821E-01	3.408737E-01	-9.157397E-02	0.0	0.0	0.0
4	G	-1.759423E-01	3.771388E-01	9.149269E-02	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 1.154776E+01

REAL EIGENVECTOR NO. 5

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	-1.369355E-01	-7.905618E-02	-3.441376E-01	0.0	0.0	0.0
2	G	1.620762E-01	9.355803E-02	-4.968914E-01	0.0	0.0	0.0
3	G	1.620103E-01	7.309171E-02	-7.571108E-02	0.0	0.0	0.0
4	G	1.443675E-01	1.036834E-01	-7.570412E-02	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

ACOSS= DRAPER STRUCTURE NOVEMBER 30, 1979 NASTRAN 6/ 7/79 PAGE 16
NOMINAL CONFIGURATION

EIGENVALUE = 1.767767E+01

REAL EIGENVECTOR NO. 6

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	2.706454E-05	2.487053E-11	6.986254E-11	0.0	0.0	0.0
2	G	-2.041393E-01	3.535484E-01	5.160320E-06	0.0	0.0	0.0
3	G	-2.041393E-01	-3.535484E-01	1.003147E-04	0.0	0.0	0.0
4	G	4.082418E-01	7.860857E-10	6.085772E-10	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 2.173488E+01

REAL EIGENVECTOR NO. 7

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	5.571241E-02	-9.646565E-02	-2.247655E-05	0.0	0.0	0.0
2	G	-3.439523E-02	5.959492E-02	-2.904864E-05	0.0	0.0	0.0
3	G	-2.881600E-02	5.643835E-02	4.873296E-01	0.0	0.0	0.0
4	G	-3.446559E-02	5.318361E-02	-4.871691E-01	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 2.261250E+01

R E A L   E I G E N V E C T O R   N O .   8

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	-7.583643E-02	-4.380433E-02	1.836695E-01	0.0	0.0	0.0
2	G	4.701469E-02	2.721628E-02	9.780988E-02	0.0	0.0	0.0
3	G	3.677456E-02	3.245069E-02	-4.696337E-01	0.0	0.0	0.0
4	G	4.655075E-02	1.565055E-02	-4.697920E-01	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 7.292165E+01

R E A L   E I G E N V E C T O R   N O .   9

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	1.445490E-01	8.346623E-02	2.702092E-01	0.0	0.0	0.0
2	G	2.125127E-01	1.227592E-01	-3.266197E-01	0.0	0.0	0.0
3	G	-1.413883E-01	-3.096361E-01	-1.503770E-02	0.0	0.0	0.0
4	G	-3.389024E-01	3.228298E-02	-1.502694E-02	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 8.557293E+01

R E A L   E I G E N V E C T O R   N O .   10

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	-5.777029E-03	9.964842E-03	-3.372035E-05	0.0	0.0	0.0
2	G	-2.241996E-01	3.882519E-01	4.517168E-05	0.0	0.0	0.0
3	G	3.846470E-01	3.681494E-02	-1.184303E-02	0.0	0.0	0.0
4	G	-2.241196E-01	-3.147115E-01	1.185495E-02	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 1.057766E+02

REAL EIGENVECTOR NO. 11

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	1.594218E-01	9.205028E-02	2.580494E-01	0.0	0.0	0.0
2	G	-1.516496E-01	-8.757726E-02	-3.116569E-01	0.0	0.0	0.0
3	G	-1.619352E-01	3.311123E-01	9.133098E-04	0.0	0.0	0.0
4	G	2.057730E-01	-3.058038E-01	9.152541E-04	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 1.665419E+02

REAL EIGENVECTOR NO. 12

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	8.369420E-02	4.832547E-02	1.586685E-01	0.0	0.0	0.0
2	G	-4.058582E-01	-2.343296E-01	-1.611017E-01	0.0	0.0	0.0
3	G	2.995676E-01	-1.419201E-01	-8.199984E-03	0.0	0.0	0.0
4	G	2.687749E-02	3.303941E-01	-8.202621E-03	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

* * * END OF JOB * * *

A.4 NASTRAN Listing for Perturbed Configuration

N A S T R A N

MSC -488

VERSION JUN 7, 1979

CDC 170 SERIES

MODEL CYBER175-2

RCS

N A S T R A N   E X E C U T I V E   C O N T R O L   D E C K   E C H O

```
ID TRUSS SIM.,BICKFORD
SOL 25
TIME 1.5
CEND
```

```
                         C A S E   C O N T R O L   D E C K   E C H O
     CARD
     COUNT
      1      TITLE = ACOSS=  DRAPER STRUCTURE
      2      SUBTITLE = PARAMETER VARIATIONS INCLUDED
      3      DISPLACEMENT = ALL
      4      SPC = 100
      5      METHOD = 100
      6      BEGIN BULK

            TOTAL COUNT=   29

*** USER INFORMATION MESSAGE 207, BULK DATA NOT SORTED,XSORT WILL RE-ORDER DECK.
```

SORTED BULK DATA ECHO

CARD COUNT	. 1 ..	2 ..	3 ..	4 ..	5 ..	6 ..	7 ..	8 ..	9 ..	10 .
1-	CONM2	21	1		4.0					
2-	CONM2	22	2		2.0					
3-	CONM2	23	3		2.0					
4-	CONM2	24	4		2.0					
5-	CROD	1	6	1	2	2	5	1	3	
6-	CROD	3	5	1	4	4	6	2	3	
7-	CROD	5	6	3	4	6	6	2	4	
8-	CROD	7	5	2	5	8	5	2	6	
9-	CROD	9	5	3	7	10	5	3	8	
10-	CROD	11	5	4	9	12	5	4	10	
11-	EIGR	100	GIV				12			+AB
12-	+AB	MASS								
13-	GRDSET							456		
14-	GRID	1		.0	.0	10.165				
15-	GRID	2		-5.0	-2.887	2.00				
16-	GRID	3		5.0	-2.887	2.00				
17-	GRID	4		.0	5.7735	2.00				
18-	GRID	5		-6.0	-1.1547	.0				
19-	GRID	6		-4.0	-4.6188	.0				
20-	GRID	7		4.0	-4.6188	.0				
21-	GRID	8		6.0	-1.1547	.0				
22-	GRID	9		2.0	5.7735	.0				
23-	GRID	10		-2.0	5.7735	.0				
24-	MAT1	15	1.0							
25-	PARAM	GRDPNT	0							
26-	PROD	5	15	150.0						
27-	PROD	6	15	1200.0						
28-	SPC1	100	123	5	THRU	10				
	ENDDATA									

TOTAL COUNT= 28

```
ACOSS=  DRAPER STRUCTURE                                            NOVEMBER  30, 1979   NASTRAN  6/ 7/79    PAGE      4
NOMINAL CONFIGURATION


   N A S T R A N   S O U R C E   P R O G R A M   C O M P I L A T I O N
DMAP-DMAP INSTRUCTION
 NO.

*** USER WARNING MESSAGE  27.
    LABEL NAMED JMPKGG   NOT REFERENCED
```

```
*** USER WARNING MESSAGE 3041

EXTERNAL GRID POINT         0 DOES NOT EXIST OR IS NOT A GEOMETRIC GRID POINT.
THE BASIC ORIGIN WILL BE USED.
```

```
                         O U T P U T   F R O M   G R I D   P O I N T   W E I G H T   G E N E R A T O R

                                              REFERENCE POINT =         0
                                                         M O
 * 1.000000E+01  0.             0.             0.             5.266000E+01  1.000000E-03 *
 * 0.            1.000000E+01   0.            -5.266000E+01   0.            0.           *
 * 0.            0.             1.000000E+01  -1.000000E-03   0.            0.           *
 * 0.           -5.266000E+01  -1.000000E-03   5.373146E+02   0.            0.           *
 * 5.266000E+01  0.             0.             0.             5.373089E+02  2.000000E-03 *
 * 1.000000E-03  0.             0.             0.             2.000000E-03  2.000057E+02 *
                                                          S
                          * 1.000000E+00  0.             0.           *
                          * 0.            1.000000E+00   0.           *
                          * 0.            0.             1.000000E+00 *
        DIRECTION
   MASS AXIS SYSTEM (S)     MASS              X-C.G.        Y-C.G.        Z-C.G.
           X              1.000000E+01        0.          -1.000000E-04  5.266000E+00
           Y              1.000000E+01        0.           0.            5.266000E+00
           Z              1.000000E+01        0.          -1.000000E-04  0.
                                                         I(S)
                          * 2.600070E+02  0.             0.           *
                          * 0.            2.600013E+02   3.266000E-03 *
                          * 0.            3.266000E-03   2.000057E+02 *
                                                         I(Q)
                          * 2.600070E+02                              *
                          *               2.600013E+02                *
                          *                              2.000057E+02 *
                                                          Q
                          * 1.000000E+00  0.             0.           *
                          * 0.            1.000000E+00   0.           *
                          * 0.            0.             1.000000E+00 *
```

E I G E N V A L U E   A N A L Y S I S   S U M M A R Y   (GIVENS METHOD)

NUMBER OF EIGENVALUES EXTRACTED	12
NUMBER OF EIGENVECTORS COMPUTED	12
NUMBER OF EIGENVALUE CONVERGENCE FAILURES . .	0
NUMBER OF EIGENVECTOR CONVERGENCE FAILURES. .	0
REASON FOR TERMINATION.	1
LARGEST OFF-DIAGONAL MODAL MASS TERM.	8.88E-15
MODE PAIR.	8
	7
NUMBER OF OFF-DIAGONAL MODAL MASS TERMS FAILING CRITERION.	0

ACOSS* DRAPER STRUCTURE
PARAMETER VARIATIONS INCLUDED

NOVEMBER 30, 1979 NASTRAN 6/ 7/79 PAGE

REAL EIGENVALUES

MODE NO.	EXTRACTION ORDER	EIGENVALUE	RADIANS	CYCLES	GENERALIZED MASS	GENERALIZED STIFFNESS
1	5	1.370434E+00	1.170655E+00	1.863156E-01	1.000000E+00	1.370434E+00
2	6	2.151447E+00	1.466781E+00	2.334455E-01	1.000000E+00	2.151447E+00
3	7	8.788939E+00	2.964614E+00	4.718331E-01	1.000000E+00	8.788939E+00
4	9	1.265757E+01	3.557748E+00	5.662332E-01	1.000000E+00	1.265757E+01
5	8	1.481010E+01	3.848389E+00	6.124902E-01	1.000000E+00	1.481010E+01
6	12	2.651650E+01	5.149418E+00	8.195553E-01	1.000000E+00	2.651650E+01
7	11	3.221590E+01	5.675905E+00	9.033485E-01	1.000000E+00	3.221590E+01
8	10	3.261330E+01	5.710806E+00	9.089030E-01	1.000000E+00	3.261330E+01
9	4	7.991696E+01	8.939628E+00	1.422786E+00	1.000000E+00	7.991696E+01
10	3	1.061638E+02	1.030358E+01	1.639866E+00	1.000000E+00	1.061638E+02
11	2	1.193202E+02	1.092338E+01	1.738510E+00	1.000000E+00	1.193202E+02
12	1	1.950677E+02	1.396666E+01	2.222864E+00	1.000000E+00	1.950677E+02

EIGENVALUE = 1.370434E+00

REAL EIGENVECTOR NO. 1

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	-2.470727E-01	4.278569E-01	1.451793E-06	0.0	0.0	0.0
2	G	-1.962626E-02	3.397530E-02	-7.213257E-06	0.0	0.0	0.0
3	G	-3.606916E-02	4.347052E-02	4.397471E-02	0.0	0.0	0.0
4	G	-1.962243E-02	5.296236E-02	-4.396723E-02	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 2.151447E+00

REAL EIGENVECTOR NO. 2

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	3.998955E-01	2.309291E-01	-1.489085E-01	0.0	0.0	0.0
2	G	8.328619E-02	4.808490E-02	6.812829E-02	0.0	0.0	0.0
3	G	6.999057E-02	2.252937E-02	-4.721041E-02	0.0	0.0	0.0
4	G	5.450509E-02	4.936097E-02	-4.721532E-02	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 8.788939E+00

REAL EIGENVECTOR NO. 3

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	6.367944E-02	3.677784E-02	4.000147E-01	0.0	0.0	0.0
2	G	1.983774E-01	1.145297E-01	2.009755E-01	0.0	0.0	0.0
3	G	1.547592E-01	6.803562E-02	9.782328E-02	0.0	0.0	0.0
4	G	1.362919E-01	1.000135E-01	9.783913E-02	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

PARAMETER VARIATIONS INCLUDED

EIGENVALUE = 1.265757E+01

REAL EIGENVECTOR NO. 4

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	2.745586E-02	-4.757822E-02	-2.249153E-05	0.0	0.0	0.0
2	G	-1.718404E-01	2.977444E-01	-6.816819E-05	0.0	0.0	0.0
3	G	-2.512485E-01	3.435807E-01	-8.190142E-02	0.0	0.0	0.0
4	G	-1.718482E-01	3.894353E-01	8.192175E-02	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 1.481010E+01

R E A L   E I G E N V E C T O R   N O .   5

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	-8.783701E-02	-5.070142E-02	-1.298769E-01	0.0	0.0	0.0
2	G	3.095025E-01	1.786358E-01	-3.514192E-01	0.0	0.0	0.0
3	G	2.865928E-01	1.224320E-01	1.139057E-02	0.0	0.0	0.0
4	G	2.493982E-01	1.868455E-01	1.140081E-02	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 2.651650E+01

REAL EIGENVECTOR NO. 6

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	1.353226E-05	1.218161E-11	3.401557E-11	0.0	0.0	0.0
2	G	-2.041393E-01	3.535484E-01	-6.057065E-06	0.0	0.0	0.0
3	G	-2.041393E-01	-3.535484E-01	1.086020E-04	0.0	0.0	0.0
4	G	4.082418E-01	6.802136E-10	5.065308E-10	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 3.221590E+01

REAL EIGENVECTOR NO. 7

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	-2.661401E-02	4.606553E-02	3.302148E-05	0.0	0.0	0.0
2	G	3.374110E-02	-5.844172E-02	3.231436E-05	0.0	0.0	0.0
3	G	2.733700E-02	-5.481037E-02	-4.912694E-01	0.0	0.0	0.0
4	G	3.381710E-02	-5.108143E-02	4.908519E-01	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 3.261330E+01

REAL EIGENVECTOR NO. 8

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	-2.993670E-02	-1.730931E-02	8.784227E-02	0.0	0.0	0.0
2	G	4.070518E-02	2.359964E-02	3.553727E-02	0.0	0.0	0.0
3	G	2.742112E-02	2.797940E-02	-4.874532E-01	0.0	0.0	0.0
4	G	3.799142E-02	9.809541E-03	-4.878664E-01	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 7.991696E+01

REAL EIGENVECTOR NO. 9

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	9.906681E-02	5.720293E-02	1.728920E-01	0.0	0.0	0.0
2	G	1.075665E-01	6.213281E-02	-4.953117E-01	0.0	0.0	0.0
3	G	-1.678804E-01	-2.198177E-01	-1.110105E-02	0.0	0.0	0.0
4	G	-2.743473E-01	-3.553812E-02	-1.108611E-02	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 1.061638E+02

R E A L   E I G E N V E C T O R   N O .   10

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	-3.389863E-03	5.849990E-03	-1.605338E-05	0.0	0.0	0.0
2	G	-2.286168E-01	3.959682E-01	4.963761E-05	0.0	0.0	0.0
3	G	3.783499E-01	4.554359E-02	-1.470533E-02	0.0	0.0	0.0
4	G	-2.286002E-01	-3.048592E-01	1.471719E-02	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 1.193202E+02

R E A L   E I G E N V E C T O R   N O .   11

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	6.369585E-02	3.677808E-02	9.588363E-02	0.0	0.0	0.0
2	G	-2.400617E-01	-1.385917E-01	-2.604959E-01	0.0	0.0	0.0
3	G	-8.625925E-02	3.944117E-01	6.969524E-03	0.0	0.0	0.0
4	G	2.984102E-01	-2.719387E-01	6.970727E-03	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

EIGENVALUE = 1.950677E+02

REAL EIGENVECTOR NO. 12

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	3.205902E-02	1.851051E-02	6.438062E-02	0.0	0.0	0.0
2	G	-4.025798E-01	-2.324354E-01	-1.304502E-01	0.0	0.0	0.0
3	G	3.203796E-01	-1.587406E-01	-9.277872E-03	0.0	0.0	0.0
4	G	2.271684E-02	3.568283E-01	-9.281694E-03	0.0	0.0	0.0
5	G	0.0	0.0	0.0	0.0	0.0	0.0
6	G	0.0	0.0	0.0	0.0	0.0	0.0
7	G	0.0	0.0	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0	0.0	0.0

* * * END OF JOB * * *

MISSION
of
Rome Air Development Center

RADC plans and executes research, development, test and selected acquisition programs in support of Command, Control Communications and Intelligence (C^3I) activities. Technical and engineering support within areas of technical competence is provided to ESD Program Offices (POs) and other ESD elements. The principal technical mission areas are communications, electromagnetic guidance and control, surveillance of ground and aerospace objects, intelligence data collection and handling, information system technology, ionospheric propagation, solid state sciences, microwave physics and electronic reliability, maintainability and compatibility.